

Tevatron Discovery Potential for Fourth Generation Neutrinos: Dirac, Majorana and Everything in Between

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(Dated: May 26, 2010)

We analyze the power of the Tevatron dataset to exclude or discover fourth generation neutrinos. In a general framework, one can have mixed left- and right-handed neutrinos, with Dirac and Majorana neutrinos as extreme cases. We demonstrate that a single Tevatron experiment can make powerful statements across the entire mixing space, extending LEP's mass limits of 60-80 GeV up to 150-175 GeV, depending on the mixing.

PACS numbers: 12.60.-i, 13.85.Rm, 14.80.-j

I. INTRODUCTION

A simple and well-motivated possibility for new physics is a fourth generation of quarks and leptons. Contrary to some previous arguments [1], such an extension of the standard model is entirely compatible with precision electro-weak data [2, 3].

Direct searches have been performed at the Tevatron for heavy fourth generation quarks (t' and b'), placing bounds of 335 GeV [4] and 338 GeV [5], respectively, on their masses. The LHC will be able to discover or definitively exclude the existence of a fourth generation of quarks up to 1 TeV [6–15].

The lepton sector, though it has great promise, has not been studied in such detail. A fourth generation of leptons may even be lighter than the fourth generation quarks, in analogy to the first three generations. In particular, the neutrino may well be the lightest new particle. Furthermore, the lepton sector is expected to be extremely rich, as the relatively high mass scale for the neutrino required by electroweak measurements suggests that the right handed neutrino of the fourth generation is not very massive. The leptonic sector therefore has two neutrino states in addition to a charged lepton.

For these reasons, it is of great interest to search for potential signals of this leptonic sector at colliders. The signals, however, are very dependent on the precise spectrum and the three mass parameters complicate the analysis. We first consider the simplest case, the limit in which the lepton and one of the neutrinos is very heavy, and the theory reduces to a single Majorana neutrino. LEP2 has placed constraints on fourth generation neutrino masses in this limit [16], depending on the decay mode of the neutrino. If the neutrino decay mode were $N \rightarrow eW$, the neutrino mass is constrained to be larger than 90.7 GeV, with corresponding bounds at 89.5 and 80.5 GeV respectively for μW and τW decay modes.

The more general case has two relatively light neutrinos of comparable mass. (We shall assume in this article that the lepton is significantly more massive than the two neutrinos and decouples; we leave its inclusion for future work.) This limit was considered in a recent paper [17] which reanalyzed the bounds from the LEP2 analysis on

this parameter space. It was shown in [17] that the LEP bounds on the neutrino mass should be weakened significantly as compared to the single neutrino case; for example, a neutrino decaying to τW could be as light as 62.1 GeV, as compared to the original bound of 80.5 GeV in the limit where only one neutrino is light (bounds were reduced to about 80 GeV for eW and μW decay modes). There is therefore a large parameter space newly opened for analysis.

This article addresses the open question of whether the Tevatron can improve these bounds in the general two-neutrino case. The Tevatron has not performed an analysis; however, a sensitivity study [18] indicated that the Tevatron could significantly improve the mass bounds on the neutrino in the one-neutrino limit. For this limit, the sensitivity study showed that, at least for the μW decay mode, the Tevatron could expect to dramatically improve the mass bounds to 175 GeV. This suggests that for the two-neutrino parameter space, the Tevatron will again have significant reach.

In this article, we present a sensitivity study for the Tevatron in the more general two-neutrino mixing space and show that in fact the neutrino mass bounds can be significantly improved. We note that previous studies have explored the possibility of searching for neutrinos at the LHC [14] and a future ILC [19]; however, a Tevatron sensitivity study has not been performed.

We begin by reviewing the theory of the two-neutrino system, and discussing the production and decay of these particles at hadron colliders. We then calculate experimental sensitivity for a selection of same-charge leptons, using Monte Carlo simulation. Finally we discuss our results and conclude.

II. PRODUCTION AND DECAY OF FOURTH GENERATION NEUTRINOS

The mass term for the two-neutrino system can be written as [17, 20]

$$L_m = -\frac{1}{2}(\overline{Q_R^c N_R^c}) \begin{pmatrix} 0 & m_D \\ m_d & M \end{pmatrix} \begin{pmatrix} Q_R \\ N_R \end{pmatrix} + h.c. \quad (1)$$

The mass eigenstates are

$$N_1 = c_\theta N_L^c + s_\theta N_R + c_\theta N_L + s_\theta N_R^c \quad (2)$$

$$N_2 = -is_\theta N_L^c + ic_\theta N_R + is_\theta N_L - ic_\theta N_R^c \quad (3)$$

with corresponding eigenvalues

$$M_1 = -(M/2) + \sqrt{m_D^2 + M^2/4} \quad (4)$$

$$M_2 = (M/2) + \sqrt{m_D^2 + M^2/4} \quad (5)$$

Here $\psi^c = -i\gamma^2\psi^*$ and $Q_R = N_L^c$. The mixing angle is related to the masses by the relation

$$\cos^2 \theta = \frac{M_2}{M_2 + M_1} \quad (6)$$

and varies over the range $\frac{1}{2} \leq \cos^2 \theta \leq 1$.

The neutrinos couple to the gauge bosons through the interaction term $L = gW_\mu^+ J^{\mu+} + gW_\mu^- J^{\mu-} + gZ_\mu J^\mu$ where

$$J^\mu = \frac{1}{2\cos\theta_W} (-c_\theta^2 \bar{N}_1 \gamma^\mu \gamma^5 N_1 - 2is_\theta c_\theta \bar{N}_1 \gamma^\mu N_2 - s_\theta^2 \bar{N}_2 \gamma^\mu \gamma^5 N_2) \quad (7)$$

$$J^{\mu+} = c_i (\bar{c}_\theta N_1 - is_\theta N_2) \gamma^\mu l_L^i \quad (8)$$

where c_i are analogous to the CKM matrix elements.

At colliders, the neutrinos can be produced either through the process $q\bar{q}' \rightarrow W^\pm \rightarrow N_i l^\pm$, where one of the fourth generation neutrinos is produced in association with a light charged lepton, or through the process $q\bar{q} \rightarrow Z \rightarrow N_i N_j$, where two heavy neutrinos are produced. There are many papers studying the reach of the Tevatron and LHC to the W process [9–12]. This is because the W production has a higher cross section at hadron colliders, and is expected to dominate. Furthermore, the mass reach is enhanced because only one heavy particle is produced in this process. On the other hand, the cross-section for the first process depends on the values of c_i , the parameters that control the mixing between the fourth generation with the first three generations. These constants are not theoretically calculable, but precision measurements suggest that this angle is small. If the mixing angle is less than about 10^{-6} , the neutrino production rates in this channel are suppressed enough that they are unobservable at colliders [9]. The rate of heavy neutrino pair-production via a Z boson, however, does not depend on the mixing parameter. We will assume that we are in the regime where this mixing angle is small, and production through an s -channel Z is the dominant production mechanism.

The decay time of the neutrinos also depend on the unknown c_i , but N_1 always decays to lW , where l is a lepton of the first three generations. We will assume that the decay happens promptly and that the neutrino does not escape or leave displaced vertices; this will happen unless the mixing angle is extremely tiny [13]. N_2 decays to lW or $N_1 Z$; the lW channel is suppressed by the small

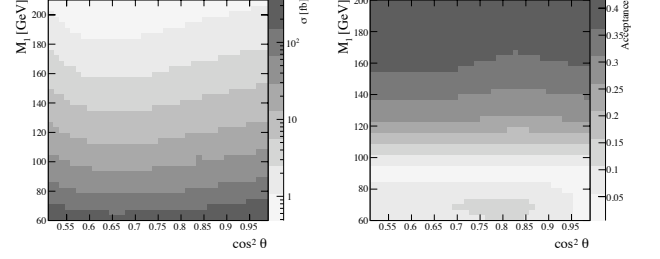


FIG. 1: Left, cross-section for $p\bar{p} \rightarrow Z \rightarrow NN$ where $NN = N_1N_1 + N_1N_2 + N_2N_2$ as a function of the N_1 mass (M_1) and the mixing angle θ . Right, acceptance of our selection, averaged over the N_1N_1, N_1N_2, N_2N_2 modes if $\text{BR}(N \rightarrow \mu W) = 100\%$.

c_i , and the $N_1 Z$ channel will dominate except if the mass difference is very small. We will assume that the mass difference is at least 1 GeV, and we assume that the CKM factor is so small that the $N_1 Z$ decay always dominates in this range.

Note that in the exact Dirac limit, N_2 must decay to lW . In this limit, the different contributions to same sign dilepton production cancel. This is expected since the Dirac fermion conserves fermion number. However, since we are assuming that N_2 always decays to $N_1 Z$ (i.e. we do not take the exact Dirac limit), there is no interference amplitude, giving same-sign dilepton decays in the entire mixing space.

We therefore consider the processes

$$pp \rightarrow Z \rightarrow N_1 N_1 \rightarrow lWlW \quad (9)$$

$$pp \rightarrow Z \rightarrow N_1 N_2 \rightarrow lWlWZ \quad (10)$$

$$pp \rightarrow Z \rightarrow N_2 N_2 \rightarrow lWlWZZ \quad (11)$$

In each case, half the decays have same sign leptons and correspondingly same sign W s.

Figure 1 shows the total cross-section for all three processes as a function of N_1 mass and mixing angle θ . Decays via a Higgs boson were also considered ($h \rightarrow N_1 N_1, h \rightarrow N_2 N_2$), but the large Higgs mass required to pair produce the heavy neutrinos makes the Higgs contribution small as compared to the production via Z .

III. EXPERIMENTAL SENSITIVITY

We study the most sensitive region, where $\text{BR}(N \rightarrow \mu W) = 100\%$. Following [18], we select events with the $\ell^\pm \ell^\pm jj$ signature:

- two like-signed reconstructed muons each with $p_T > 20$ GeV and $|\eta| < 2.0$
- at least two reconstructed jets, each with $p_T > 15$ GeV and $|\eta| < 2.5$

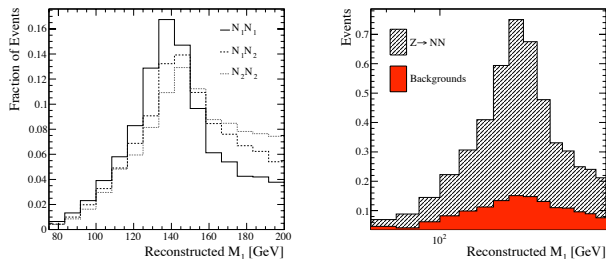


FIG. 2: For $M_1 = 150$ GeV, and $\cos^2\theta=0.67$. Left, reconstructed M_1 in selected events with for $N_1 N_1, N_1 N_2, N_2 N_2$ modes. Other masses and mixing angles are qualitatively similar. Right, expected signal and backgrounds in 5/fb of CDF data.

The efficiency of the selection is shown in Figure 1 and is a strong function of N_1 mass; when $M_1 - m_W$ is small, the lepton from the $N_1 \rightarrow lW$ decay has small transverse momentum and is difficult to reconstruct.

We reconstruct one or two N_1 masses in each event using all m_{jjl} combinations where m_{jj} is consistent with a hadronic W decay. Figure 2 shows the reconstructed N_1 mass shape for the $N_1 N_1, N_1 N_2$, and $N_2 N_2$ modes.

At CDF, the largest backgrounds to the $\ell^\pm \ell^\pm jj$ signature come from $W\gamma$ or WZ production or misidentified leptons [21] either from semi-leptonic $t\bar{t}$ decays or direct W + jets production. As in [18], we extrapolate the number of expected background events in 1 fb^{-1} [21] to a dataset with 5 fb^{-1} , use MADGRAPH [22] to model the kinematics of the events, PYTHIA [23] for showering and a version of PGS [24] tuned to describe the performance of the CDFII detector. Figure 2 shows the expected signal and backgrounds in 5 fb^{-1} of CDF data. We perform a binned likelihood fit in the reconstructed N_1 mass, and use the unified ordering scheme [25] to calculate median expected limits from frequentist intervals.

We present the expected Tevatron constraints in the $(M_1, \cos^2\theta)$ plane in Fig 3. The shaded regions show regions that can be excluded by a Tevatron search, assuming $\text{BR}(N \rightarrow \mu W) = 100\%$.

The shape of the constraints can be understood as follows. In the limit $\cos^2\theta = 1$, M_2 is infinite, and we return to the one-neutrino case. As $\cos^2\theta$ decreases, the mixing angle between the Z and the lighter neutrino is reduced, leading to a smaller cross-section and therefore a weakening of the bounds. On the other hand, as $\cos^2\theta$ decreases, the heavier neutrino mass is also reduced (when $\cos^2\theta = 1/2$, the neutrinos are degenerate); as a consequence, as we reduce $\cos^2\theta$ from 1 to $1/2$, the heavier neutrino eventually becomes light enough that it is accessible to production. At this point, the bounds again improve. The mass exclusion therefore weakens and then strengthens as a function of $\cos^2\theta$. Furthermore, at lower values of M_1 , there is a gap which is not excluded by our study. This occurs because the leptons from $N \rightarrow lW$

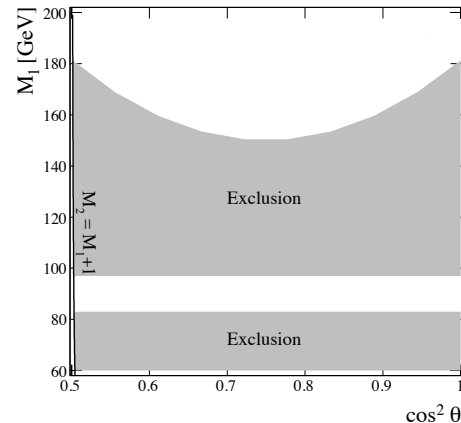


FIG. 3: Expected 95% C.L. exclusion regions for 5 fb^{-1} of CDF data, as a function of the N_1 mass and the mixing angle θ .

become very soft, and fall below the p_T cut.

For $\cos^2\theta$ very close to $1/2$, we approach the Dirac limit. In this limit, the decay $N_2 \rightarrow N_1 Z$ may open up (depending on the mixing between the fourth and the other generations). We therefore impose the condition $M_2 > M_1 + 1$. There is thus a narrow strip on the left of the plot which is excluded from our analysis.

Our analysis has assumed that the neutrino only decays to μW . If the neutrino decays to eW or τW as well, the limits will be degraded. This was analyzed for the one-neutrino case in [18] and it was shown how the limits are reduced. Since we describe the identical selection here, our limits will degrade in the same manner.

IV. CONCLUSIONS

We have shown that the Tevatron has a significant reach to fourth generation neutrinos, and can place significant constraints on the general two-neutrino parameter space. Quantitatively, if the N_1, N_2 do not exist and no excess is seen, CDF can exclude the existence of N_1, N_2 up to 150-170 GeV, depending on the mixing angle, with the exception of a band between 83-97 GeV, where the acceptance is very small due to the softness of the produced lepton. This makes a strong case to search for potential signals of these neutrinos in the current dataset.

These results leave open several interesting directions for future research. Perhaps the most difficult and important is to cover the gap where the neutrino mass is close to the W mass by understanding the backgrounds to very soft leptons. In addition, we hope to include the charged leptons in future studies.

V. ACKNOWLEDGEMENTS

We acknowledge discussions with L. Carpenter and T. Tait. A.R. is supported in part by NSF Grant No.

PHY-0653656. D.W. is supported in part by the U.S. Dept. of Energy.

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